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β Cephei stars in the ASAS-3 data

I. Long-term variations of periods and amplitudes

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ABSTRACT

Aims. We analyse V-filter ASAS-3 photometry of 41 known β Cephei-type stars. The ASAS-3 photometry is combined with the archival data, if available, to determine long-term stability of periods and amplitudes of excited modes.
Methods. Frequencies of modes are derived by means of Fourier periodograms with consecutive prewhitening. The results are examined in the context of detection threshold.
Results. We detected amplitude changes in three β Cephei stars, BW Cru, V836 Cen, and V348 Nor. Period changes were found in KK Vel and V836 Cen. Our analysis shows that intrinsic period changes are more common among multiperiodic stars, apparently because they are caused by some kind of mode interaction. In addition, we found new modes for seven stars, and for ten others we provide new solutions or remove ambiguities in the detected frequencies. One candidate hybrid β Cephei/SPB star, HD 133823, is discovered.

Key words. Stars: early-type – Stars: oscillations – Surveys

1. Introduction

A group of main-sequence early B-type pulsating stars, known as β Cephei stars, has been studied for over a hundred years. The discovery of the mechanism driving pulsations in these stars (Moskalik & Dziembowski 1992; Dziembowski & Pamyatnykh 1993; Pamyatnykh 1999) advanced our understanding of their nature and opened the possibility of addressing more complex questions concerning their pulsations. In particular, studies by means of asteroseismology became possible. The attractiveness of β Cephei stars for asteroseismology results from the fact that – as pulsators – they are neither too simple nor too complex. It is also one of the first groups of pulsating stars in which nonradial pulsations were studied in detail, as nonradial pulsations are for them the rule than the exception. Moreover, typically less than a dozen modes are observed in a single star which seems to be a sufficient number in seismic modeling.

The properties of β Cephei stars have recently been summarised in a review paper of Stankov & Handler (2005). Among other topics, these authors discussed the boundaries of the instability strip of β Cephei stars and pulsations in O-type stars. There are many more interesting, yet still not well understood problems related to β Cephei stars, for example, their relation to other variable stars in the upper main-sequence, influence of fast rotation on pulsations, dependence on metallicity. One such problem, the long-term stability of periods and amplitudes in these stars, is addressed in the present paper.

A reliable study of long-term changes of periods and/or amplitudes requires long-time data with a good coverage. There are many β Cephei stars that show stable pulsation(s) on a time scale of decades. Only a handful are known for their variation of period and/or amplitude (Jerzykiewicz & Pigulski 1998; Jerzykiewicz 1999). Sometimes, the variation is fast enough to be detected using only observations from two consecutive seasons. As possible causes of the period variation include evolutionary effects and mode interaction, these changes merit being studied.

An all-sky survey covering several years of observations offers an excellent opportunity to detect period and amplitude changes, especially if the data can be combined with the archival ones. In the present paper we take advantage of such an opportunity by analysing the photometry obtained within the ASAS-3 survey for all known β Cephei stars in the magnitude range it covered.

2. ASAS

Photometric surveys, especially those that cover large parts of the sky, provide an unprecedented chance of studying different classes of variable stars. One such survey, the All Sky Automated Survey (ASAS, Pojmański 1997, 2000; Pojmański et al. 2005, and references therein), already covers about 70% of the whole sky. Nineteen new large-amplitude β Cephei stars were recently found using the published ASAS catalogues (Pigulski 2005; Handler 2005).

Due to the method of selection, however, the published ASAS catalogues are biased towards large-amplitude variables. Most of the nineteen β Cephei stars found in the ASAS-2 and ASAS-3 data by Handler (2005) and Pigulski (2005, hereafter P05) have semi-amplitudes larger than 30 mmag, i.e., quite large for β Cephei stars. On the other hand, the typical detection threshold of the ASAS data for stars brighter than 10 mag

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amounts to semi-amplitudes of about 3–5 mmag. The 19 above-mentioned large-amplitude β Cephei stars represent therefore the tip of an iceberg and it was obvious that many more such stars can be found in the ASAS data.

With this paper we start publication of the results of searching for β Cephei stars in the complete ASAS-3 database, i.e., among stars that presently are not included in the published ASAS catalogues. Since many known β Cephei stars fall into the magnitude range of the ASAS-3 observations, we first publish the results of an analysis of the ASAS-3 photometry for known β Cephei stars. This is the subject of the present paper. Combining the ASAS-3 and archival data, we discuss here the frequency contents of their pulsation spectra and the long-term stability of the amplitudes and periods. The remaining two papers of the series will contain the main results, namely the discovery of ~280 β Cephei stars. The first part, 103 new β Cephei stars, is presented in the accompanying paper (Pigulski & Pojmański 2007, hereafter Paper II) where we also discuss the presence of low-frequency modes in these stars. The third paper of the series will contain data for the remaining ~180 β Cephei stars found in the ASAS-3 data and a discussion of the distribution of all known stars of this type in the Galaxy.

3. The data

The ASAS started in 1996 with the test phase, ASAS-1 and ASAS-2 (Pojmański 1997, 1998, 2000), which covered only selected areas in the southern sky and equatorial regions. However, the first catalogue already included about 4000 bright variable stars (Pojmański 2000). A general description of the properties of the ASAS-1 and ASAS-2 data and new automatic classification for this catalogue was provided by Eyer & Blake (2005).

During the ongoing, third part of the survey, ASAS-3 (Pojmański 2001), started at the end of 2000, the whole southern sky and partly the northern sky, up to declination +28°, is monitored. ASAS-3 provides photometry for about 15×10^6 stars in the range between 7 and 14 mag. The accuracy of a single measurement amounts to about 8 mmag for a star with $V \sim 8$ mag, 13 mmag for a star with $V \sim 10$ mag, then increases rapidly.

By means of a magnitude-dispersion diagram, about 50 000 variable stars were selected using the ASAS-3 V-filter data. The stars were classified automatically and included in the catalogue that is published (Pojmański 2002, 2003; Pojmański & Maciejewski 2004, 2005; Pojmański et al. 2005). The nineteen new β Cephei stars mentioned above were found among stars included in this catalogue.

In the ASAS-3 data, typically a single measurement per night or two nights was obtained for a given star. This means that frequencies typical for β Cephei stars are located well above the Nyquist frequency. Fortunately, the data are not distributed ideally evenly in time. Consequently, the repeatable structure that for evenly distributed data appears over the Nyquist frequency, does not occur in the Fourier periodograms of the ASAS-3 data which were calculated in the interval between 0 and 40 d^{-1}. The most severe problem with proper identification of frequencies in the periodgrams of the ASAS-3 data was, as could be expected, related to the daily aliases. This can be seen in Fig. 1 where the spectral window of a typical ASAS-3 data is shown. On the other hand, yearly aliases are quite low in the ASAS-3 data (top panel of Fig. 1). This is a consequence of the fact that a given field was observed for almost the whole year provided that it stood relatively high above the horizon during the night. This means that long gaps in the ASAS-3 data occur only for stars located relatively close to the ecliptic and, due to location of the site (Las

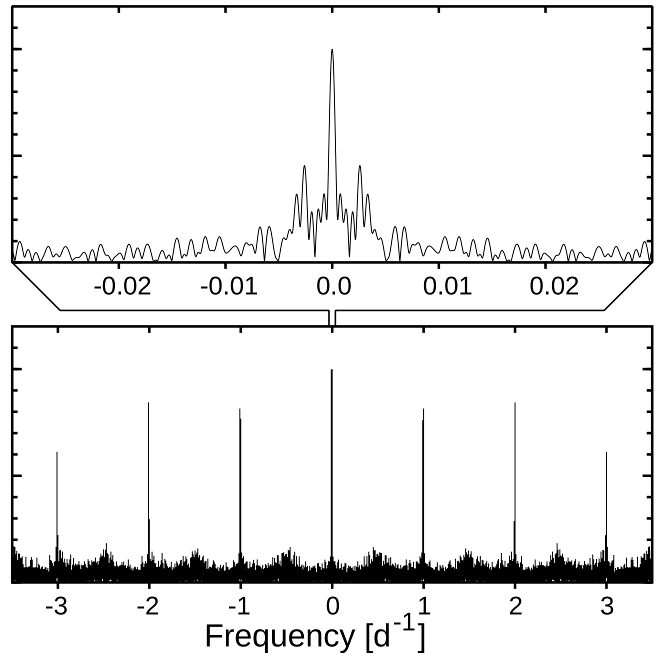

Fig. 1. Spectral window of a typical ASAS-3 data. Note that the yearly aliases at ±0.0027 d^{-1} (top panel) are relatively low. Ordinate is the amplitude in arbitrary units.

Campanas Observatory, Chile), for stars with positive declinations. The low yearly aliases in the periodograms of the ASAS-3 data are advantageous for correct frequency identification. While daily aliases can be easily removed with a short follow-up multi-site campaign, in order to remove the ambiguity in yearly aliases, much longer campaigns would be required.

The spatial resolution of the ASAS-3 data is defined by the detector scale which amounts to about 14″ per pixel. For this reason, the ASAS-3 data are not well suited for the study of stars in open clusters. Nevertheless, as we will show below, some information on variability can be obtained from the ASAS-3 data even for stars in clusters or other dense fields. However, a strong contamination by nearby stars and larger photometric errors can be expected in this case.

The ASAS-3 V-filter photometry analysed in this paper covers the interval between the beginning of the project in 2000 and the end of February 2006.[1]

4. Stars showing long-term period changes

The recently published catalogue of β Cephei stars (Stankov & Handler 2005) contains 93 objects. Of these, many fall within the magnitude range covered by the ASAS-3 data. We present the results of analysis for 22 of them, i.e., all that have reasonably good photometry in ASAS-3. The remaining are: (i) too bright, (ii) too faint, (iii) north of declination +28°, (iv) in dense fields, e.g., open clusters. We also add a new analysis for 19 stars found with the ASAS data. Four were found in the I-filter ASAS-2 data (Handler 2005). For the remaining 15, some new V-filter observations were obtained since the time of publication of the ASAS-3 data. General properties of all 41 stars under consideration are summarised in Table 1. The results of sine-curve fits are presented in Table 2, 3 and 4 available as online material.

[1] The V photometry for all 103 stars is available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/??/??

Table 1. Known β Cephei stars with good ASAS-3 photometry. N stands for the number of independent modes found in the ASAS-3 photometry, the remaining columns are self-explanatory.

HD	CPD/BD	ASAS name	Other name	N	V [mag]	$B-V$ [mag]	$U-B$ [mag]	MK sp. type [a]	Notes
59864	−33°1536	073034−3405.4	V350 Pup	1	7.62	−0.09	−0.83	B2 II [1]	Ambiguity resolved
71913	−34°2531	082843−3443.9	YZ Pyx	1	7.68	−0.11	−0.82	B1/2 II [2]	
78616	−44°3436	090742−4438.0	KK Vel	1	6.77	−0.01	−0.75	B2 III [1]	Period changes
80383	−52°2185	091731−5250.3	IL Vel	2	9.14	+0.04	−0.66	B2 III [3]	
90288	−56°3250	102357−5727.8	V433 Car	2	8.14	−0.15	−0.90	B2 III/IV [4]	
303067	−57°3486	103530−5812.1	V401 Car	1	9.54	+0.03	−0.76	B1.5 III [5]	
—	−57°3500	103541−5812.7	V403 Car	1	8.74	0.00	−0.81	B1 III [5]	Ambiguity resolved
109885	−70°1502	123920−7137.3	KZ Mus	3	9.02	+0.13	−0.66	B2 III [4]	
—	−59°4564	125358−6025.0	BW Cru	1	9.07	+0.10	−0.70	B2 III [6]	Amplitude change
112481	−49°5591	125736−4946.9	V856 Cen	1	8.35	+0.05	−0.76	B2 II/III [3]	
129929	−36°6541	144626−3713.4	V836 Cen	5	8.09	−0.18	−0.87	B3 V [7]	Ampl. & period changes
145794	−52°9416	161526−5255.3	V349 Nor	2	8.76	+0.24	−0.62	B1 V [1]	
147985	−43°7557	162657−4347.9	V348 Nor	2	7.95	+0.14	−0.64	B1/2 II/III [3]	Amplitude change
156327	−34°6800	171823−3424.5	V1035 Sco	3	9.35	+0.62	−0.11	WC7 + B0 III [8]	New mode
156662	−45°8479	172106−4558.9	V831 Ara	3	7.83	+0.17	−0.66	B2 III [3]	Ambiguity resolved?
157485	−26°5889	172435−2655.5	V2371 Oph	2	9.07	+0.56	−0.30	B1/2 Ib [2]	
164340	−40°8357	180233−4005.2	NSV 24078	4	9.28	−0.14	−0.95	B0 III [9]	New mode
165812	−22°6732	180845−2209.6	V4382 Sgr	3	7.94	+0.01	−0.79	B1.5 II [1]	New mode, ambiguity resolved
166540	−16°4747	181148−1653.6	V4159 Sgr	5	8.14	+0.16	−0.73	B0.5 IV [10]	
180642	+00°4159	191715+0103.6	V1449 Aql	1	8.27	+0.22	−0.66	B1.5 II-III [11]	
203664	+09°4973	212329+0955.9	SY Equ	1	8.57	−0.20	−1.00	B0.5 III(n) [11]	
—	−19°8282	223738−1839.9	HN Aqr	1	11.46	—	—	B1 [12]	
—	−62°2707	122213−6320.8	ALS 2653	1	10.06	+0.08	−0.68	B2 III [1]	
133823	−65°2993	150955−6530.4		4	9.62	+0.05	−0.66	B2 IV [1]	New mode, hybrid object
—	−50°9210	161858−5103.4	ALS 3547	3	10.33	+0.46	−0.49	B2 II [13]	New mode
328862	−47°7861	164409−4719.1	ALS 3721	3	10.13	+0.27	−0.51	B0.5 III [14]	
—	−46°8213	164630−4701.2		1	10.86	+0.56	−0.39	—	New mode
328906	—	164939−4431.7		2	11.22	—	—	B2 [15]	
152077	−43°7731	165314−4345.0	ALS 3793	3	9.08	+0.29	−0.58	B1 II [1]	
152477	−47°7958	165554−4808.8		1	9.04	+0.66	−0.28	B1 II [1]	
155336	−32°4389	171218−3306.1	ALS 3961	3	9.46	+0.25	−0.59	B1/2 Ib [2]	New solution
165582	−34°7600	180808−3434.5	ALS 4668	4	9.39	0.00	−0.80	B1 II [1]	New solution
167743	−15°4909	181716−1527.1		3	9.69	+0.35	—	B2 Ib [16]	
—	—	182610−1704.3	ALS 5036	2	10.21	+0.59	−0.42	—	
—	—	182617−1515.7	ALS 5040	3	10.75	+0.47	−0.51	—	New solution
—	−14°5057	182726−1442.1		1	9.97	+0.51	−0.31	—	
100495	−62°2096	113318−6306.2	ALS 2386	3	9.63	+0.15	−0.70	B1 III [3]	New mode
—	−61°3314	123748−6219.4	ALS 2714	4	10.23	+0.44	−0.52	—	
—	—	125319−6401.4	ALS 2798	3	11.65	+0.92	−0.15	—	
—	—	130220−6328.4	ALS 2877	2	11.35	—	—	—	
191531	+20°4449	200940+2104.7		1	8.40	−0.09	—	B0.5 III-IV [11]	

[a] References to the MK spectral types: [1]–Garrison et al. (1977), [2]–Houk (1982), [3]–Houk (1978), [4]–Houk & Cowley (1975), [5]–Evans et al. (2005), [6]–Schild (1970), [7]–Hill (1970), [8]–Lépine et al. (2001), [9]–Hill et al. (1974), [10]–Morgan et al. (1953), [11]–Walborn (1971), [12]–Kilkenny et al. (1977), [13]–FitzGerald (1987), [14]–Whiteoak (1963), [15]–spectral type on the Harvard system, Nesterov et al. (1995), [16]–Houk & Smith-Moore (1988).

In addition, Fourier periodograms showing consecutive steps of prewhitening are presented in Figs. 2–6, also available online.

Combining the ASAS-3 and archival photometry, we have found period variations in two stars, KK Vel and V836 Cen. These findings are described in this section. For V836 Cen and two other stars, BW Cru and V348 Nor, we also found long-term variations of the amplitude (Sect. 5). The other individual stars, especially their periods and amplitudes are commented on in Appendix A. For these stars, we did not find long-term changes of periods and amplitudes either because they are stable in the time covered by observations or the data are too scarce to allow that. However, from the ASAS-3 observations we found new modes in seven stars; for ten others we provide new solutions or resolve ambiguities in their frequencies. This is commented on in the last column of Table 1.

4.1. KK Vel = HD 78616 = HIP 44790

The star was used as a standard for UBV photometry in the Harvard E4 field. Its variability was previously suspected by Cousins & Stoy (1962), but confirmed by T. Lloyd Evans in 1980 as reported by Cousins (1982). Cousins (1982) indicated also a non-sinusoidal shape of the light curve and possible period changes. Heynderickx (1992) analysed new Geneva and Walraven photometry of this star, also detecting a single non-sinusoidal mode. We recovered a single periodicity with a harmonic both in the Hipparcos and the ASAS-3 data. The presence

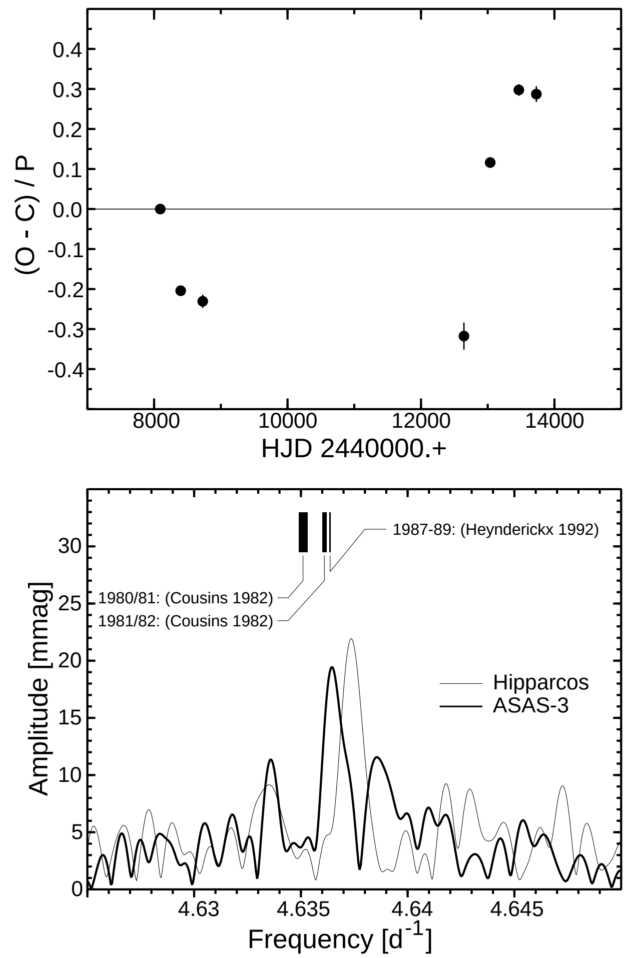

Fig. 7. *Top:* The O-C diagram for the main mode of KK Vel from the Hipparcos and ASAS-3 data. *Bottom:* Fourier periodograms of the Hipparcos (thin line) and ASAS-3 data (thick line) of KK Vel in the vicinity of the main peak. For comparison, frequencies reported in the literature are shown with short vertical lines. The widths of the lines correspond to the doubled r.m.s. errors of the frequencies.

of a harmonic seems to be a little surprising in a star with not-so-large amplitude, but it has to be remembered that KK Vel is a visual double. The secondary is just 0.″3 distant and relatively bright, so that the observed amplitude is reduced. After removing the contribution from the main signal and its harmonic we still detect a strong signal at a frequency very close to the main frequency (online Fig. 2). There is also a high peak close to the main frequency in the periodogram of the residuals in the Hipparcos data. We have split Hipparcos and ASAS-3 data into seven subsets and derived amplitudes and times of maximum light for each subset independently. The derived amplitudes are constant within the errors, while the O-C diagram (Fig. 7) clearly reveals changes of period. As mentioned above, the presence of period changes in this star was already indicated by Cousins (1982). He found that the 1980–81 observations can be represented with a frequency of 4.6351 ± 0.0002 d^{-1}, but 1981–82 data are best fitted with a frequency of 4.6361 ± 0.0001 d^{-1}. The changes of period can be also seen directly in a comparison of the periodograms of the Hipparcos and ASAS-3 data (Fig. 7). Unfortunately, the existing data do not allow us to trace these changes in detail. It is worth noting, however, that the presence of the visual companion of KK Vel may contribute to the apparent period changes via the light-time effect like in β Cep (Pigulski & Boratyn 1992), σ Sco (Pigulski 1992), and possibly BW Vul (Pigulski 1993).

4.2. V836 Cen

Since the amplitude changes in V836 Cen are better pronounced than period changes, a detailed description of the analysis of the ASAS and archival data for this star is given in Sect. 5.1. Of the six modes observed in V836 Cen only one seems to be relatively stable (Fig. 9). The remaining show cyclic or even more complex behaviour. A similar character of period changes is observed in 12 Lac (Pigulski 1994). Both stars are similar in the sense that they have several modes with considerable amplitudes. There is no simple explanation of the period changes seen in V836 Cen, we can only speculate that they might be caused by some kind of mode interaction. This is discussed further in Sect. 6.

5. Stars with long-term amplitude changes

The most interesting star showing detectable amplitude changes is V836 Cen. In addition, we were able to detect amplitude changes in two other stars, BW Cru and V348 Nor.

5.1. V836 Cen = HD 129929 = HIP 72241

The variability of HD 129929 was discovered by Rufener (1981, see also Rufener & Bartholdi (1982)). Waelkens & Rufener (1983) found three periodic terms in the photometry of this star. Heynderickx (1992) also found three significant modes, but their periods did not agree well with those of Waelkens & Rufener (1983). Aerts et al. (2004b, hereafter A04) combined data obtained by previous investigators and new ones. The dataset analysed by these authors consisted of 21 years of observations in the seven-band Geneva photometric system. Their analysis yielded six independent modes including equally-spaced triplet around 6.98 d^{-1} and a doublet with the same spacing around 6.46 d^{-1}. The possibility of the presence of additional low-amplitude modes was also indicated by A04.

The first mode we detected in the ASAS-3 data was the f_6 mode in the Aerts et al. (2004b) notation (we will use this notation for V836 Cen throughout this section), i.e., the mode which had the smallest amplitude of the six modes that were found in the Geneva data. The next two modes we detected were f_3 and a mode with a frequency of 6.97767 d^{-1}. This is very close to f_2 = 6.978305 d^{-1} (A04), but is significantly different from it. We temporarily adopt 6.97767 d^{-1} as the true frequency. The periodogram with three modes subtracted revealed daily aliases of f_1 and f_4. However, both were at the limit of detection as the signal-to-noise (S/N) ratio for these peaks amounted to 4.0. The f_5 mode was not detected at all.

In view of the suspected amplitude changes in V836 Cen, we decided to re-analyse the Geneva data and check the stability of the amplitudes of the modes. Along with the ASAS-3 photometry made in the years 2000–2006, the *V*-filter data for this star already cover about 30 years and are reasonably well distributed over this interval. First, we split the *V*-filter Geneva data into three subsets covering the intervals: 1974–1982, 1985–1989, and 1992–1995, the fourth set consisting of the ASAS-3 photometry. Each set was then analysed independently. We fitted all six modes with frequencies given by A04. In addition, we allowed *linear* amplitude changes within each subset. The amplitudes, the rates of amplitude change, phases and frequencies were improved by means of a non-linear least-squares fit. At this

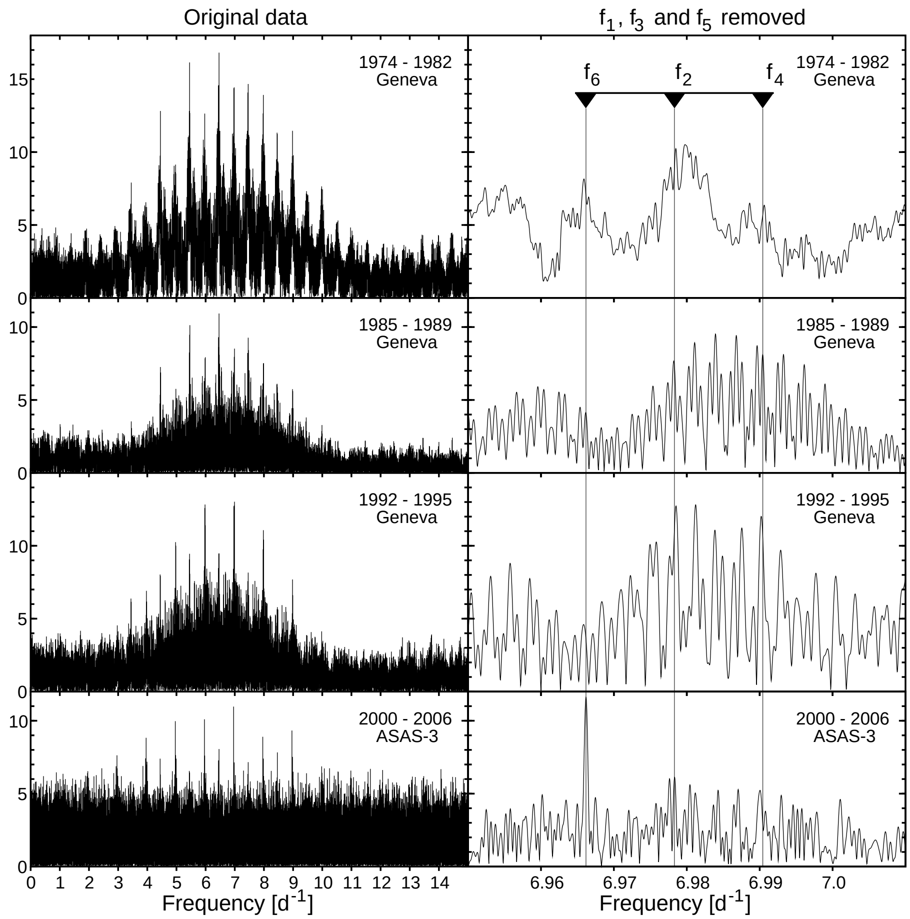

Fig. 8. *Left:* Fourier periodograms of the *V*-filter data of V836 Cen calculated separately for four subsets defined in the text. The ordinate is the amplitude in mmag. *Right:* Periodograms of the same subsets prewhitened with f_1, f_3, and f_5. Only a narrow frequency range around 6.98 d^{-1} is shown. This is the region where the remaining three modes, with equally split frequencies, occur. They are labelled as f_6, f_2, f_4 and indicated with thin vertical lines. Note the differences in the frequency pattern, which we interpret as evidence for amplitude changes.

step, we also removed some year-to-year trends present in the Geneva data as they produced high signal at low frequencies in the periodograms.

The analysis showed convincingly that (i) there are large differences in the amplitudes of modes for different subsets, as can be seen in Fig. 8, (ii) the rates of amplitude change are significantly different from zero for some mode/subset combinations. Note that the differences in frequency patterns for two different datasets of V836 Cen were already indicated by Heynderickx (1992) when he compared his results with those of Waelkens & Rufener (1983).

The question which arises now is the time scale of the amplitude changes. The periodogram of the residuals from the solution mentioned above showed significant peaks close to frequencies that were removed, leading us to suspect that the time scale of the amplitude changes might be shorter than the length of a subset, i.e., 3–8 years. The other reason for the presence of these peaks might be period changes. In order to trace the changes of amplitudes on a shorter time scale, we proceeded in the following way. We used the solutions mentioned above, i.e., solutions that allowed linear amplitude changes and were calculated for each subset independently, to remove the contribution from all modes but f_1. The residuals were then split into 13 shorter subsets, in most cases covering a single season. For each such subset, a sinusoid with frequency equal to f_1 was fitted in order to derive the amplitude and the time of maximum light. A similar procedure was then applied to all six modes. The resulting semi-amplitudes are shown in Fig. 9. We stress that the procedure we used is not equivalent to fitting a six-mode model to the seasonal data. This would lead to the well-known problems with resolution and aliasing. Instead, it takes advantage of the fact that the frequency contents is known from the best data and that–when we are left with only one mode not subtracted–its amplitudes and phases can be traced in a yearly time scale. In addition, it can be believed that the other modes are subtracted quite correctly because they were all included in the model used for subtraction. This model, in turn, was fitted to the dataset which had the time-span long enough to avoid problems with frequency resolution.

It can be clearly seen from Fig. 9 that the amplitude is roughly constant only for f_3 and f_5. For f_1, it is decreasing steadily, while for the triplet components, f_2, f_4, and f_6, it seems to change less regularly, and large differences in amplitude can be seen from season to season.

We performed another cross-check of the amplitude changes using two subsets of the Geneva data, 1988–1989 and 1992–1995, and consecutively extracted modes that appeared in the periodograms. As expected, for each subset the modes were recovered in the order consistent with the amplitudes shown in Fig. 9. In addition, a double peak was found close to f_2 in the periodogram of the 1992–1995 data. This is simply a consequence of a large drop in amplitude between 1992/3 and 1994/5 (Fig. 9). The amplitude change also explains the occurrence of a double peak near f_2 in the analysis of the ASAS-3 data (see Fig. 8) as the amplitude of f_2 has dropped significantly in the time interval covered by these observations.

Having derived the amplitudes and phases, we were left with the residuals that were used to check the correctness of the fit. The Fourier periodogram of these residuals is shown in Fig. 10. The highest peak occurs at frequency 3 d^{-1} and is likely to be due to the residual extinction unaccounted for in the Geneva data. No other significant peaks appear above the 1.5 mmag level, even in the region where the frequencies of the six modes were found

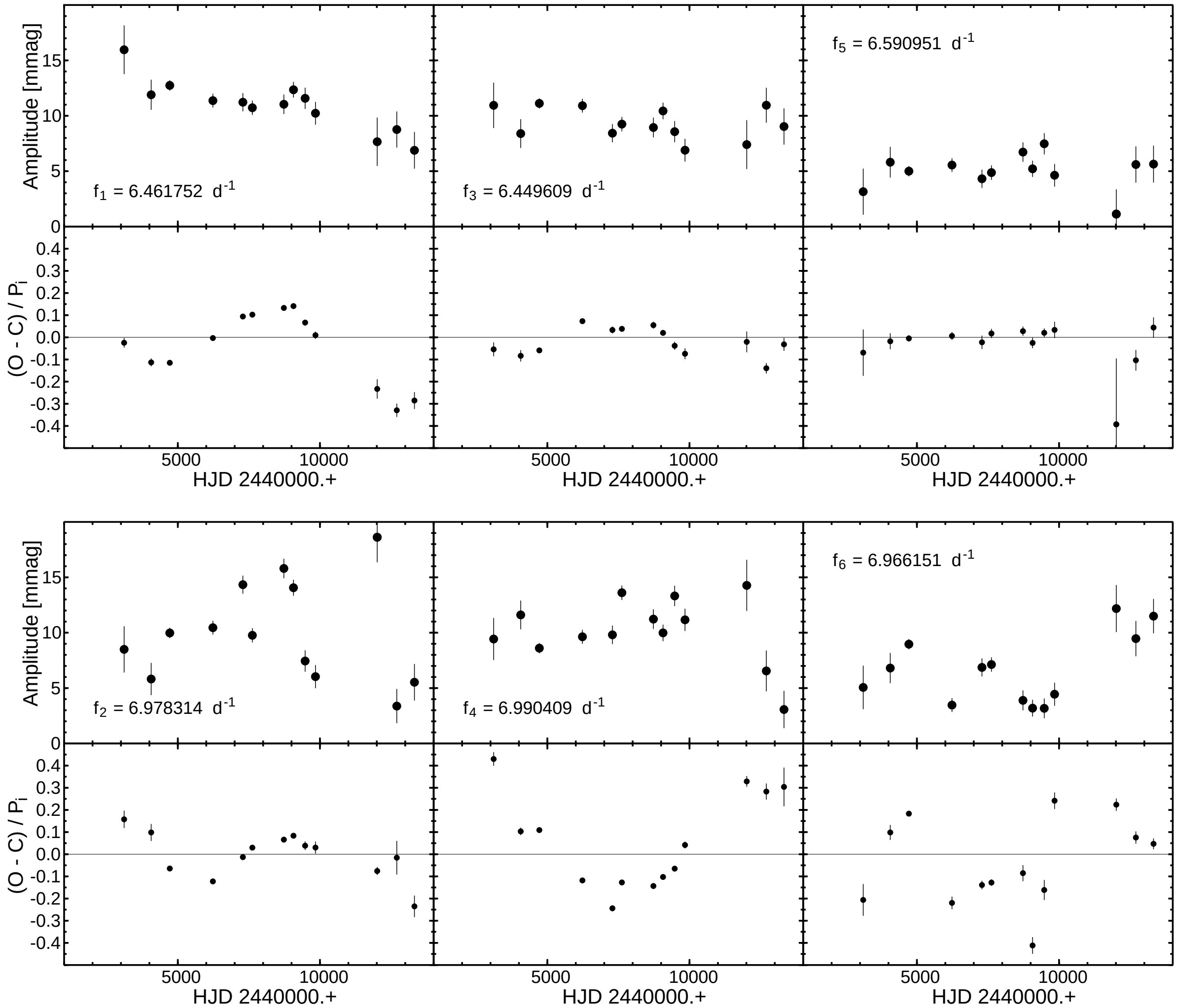

Fig. 9. V-filter semi-amplitudes and O−C diagrams for six modes of V836 Cen. The ordinate range in the O−C diagrams equals the length of the corresponding period.

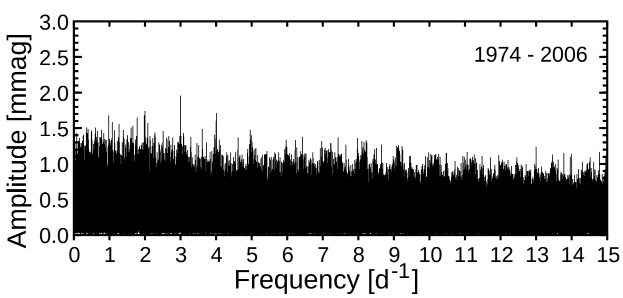

Fig. 10. Fourier periodogram of the residuals from the final solution of V836 Cen data in the V filter.

(6.5–7 d^{-1}). We therefore conclude that the changes of amplitudes and phases of the six modes shown in Fig. 9 fully describe the photometric variability of V836 Cen. The occurrence of residual power and additional low-amplitude modes (f_7 and f_8) in the 6–7 d^{-1} range, mentioned by A04, were simply a consequence of neglecting the possibility of amplitude changes.

Since the amplitudes of the pulsation modes in V836 Cen were used for mode identification, it is reasonable to check if the changes of amplitudes and phases in other filters follow the pattern found in the V filter. We therefore made a similar analysis of the Geneva data in the remaining six filters. The results confirm the character of the changes seen in the V filter. Except for the six modes found by A04, no others were detected. The detection threshold in the 5–10 d^{-1} range, defined as the mean amplitude in the Fourier spectrum of residuals multiplied by 4, was equal to 2.2 mmag in U, 1.7 mmag in B, B_1, B_2 and V_1, 1.4 mmag in V, and 1.8 mmag in G. The semi-amplitudes and times of maximum light are presented in Table 6, and are available as online material.

The parameters, particularly the amplitudes in different filters derived by A04, were later used for seismic modelling of V836 Cen (Dupret et al. 2004). Since all Geneva data were made simultaneously in all seven filters, one may expect that the fact that their amplitudes are changing did not affect the amplitude ratios. This is indeed the case. For completeness, in Table 5 we provide the amplitude ratios calculated as weighted means of the ten ratios obtained from the subsets covered by the Geneva data.

5.2. BW Cru = HIP 62949 = NGC 4755-F

The star, a member of the open cluster NGC 4755, was noted to have variable radial velocity by Hernández (1960). Its photometric variability was discovered by Jakate (1978) who found a period of 0.203 d, corresponding to frequency of about 4.9 d^{-1}. The star was later studied by Shobbrook (1984) and Koen (1993)

who confirmed its variability. Koen (1993) found two periodic terms with frequencies 4.89 and 6.16 d^{-1}. The latter frequency was not found in the data analysed by Balona & Koen (1994) and Stankov et al. (2002). The accurate photometry of Stankov et al. (2002) resulted in the confirmation of the known mode with frequency of 4.88 d^{-1}. Stankov et al. (2002) also discovered two new modes with frequencies 4.54 and 5.27 d^{-1}.

In the ASAS-3 data, we detect only the main mode with frequency 4.88458 ± 0.00004 d^{-1} and the V-filter semi-amplitude equal to 10.3 ± 1.2 mmag (Fig. 3). The other modes are not detected because our detection threshold amounts to about 6 mmag. It is interesting to note that the amplitude of the main mode, despite probable contamination by nearby stars, is larger than the values derived previously: 7 mmag (Koen 1993), 6.4 ± 0.5 mmag (Balona & Koen 1994), 6.4 ± 0.8 (Balona et al. 1997), but agrees quite well with the value of 9.6 ± 1.1 mmag, derived by Stankov et al. (2002). We conclude that the main mode in BW Cru undergoes a long-term increase of amplitude.

5.3. V348 Nor = HD 147985 = HIP 80563

The star was found to be β Cephei-type variable by Waelkens & Cuypers (1985). These authors found three periodicities with frequencies 7.5579, 6.8999, and 6.3834 d^{-1} in their 1983 observations, carried out in the seven-band Geneva system. The V-filter semi-amplitudes of these three modes were equal to 23, 12.5 and 7 mmag, respectively.

In the ASAS-3 data, we detect only two modes (Fig. 4). The first detected mode is the mode at 6.90033 d^{-1} which has semi-amplitude equal to 10.8 ± 0.8 mmag, in reasonable agreement with 12.5 mmag in the Geneva data. The other, with frequency of 7.55795 d^{-1}, has an amplitude of only 5.4 ± 0.8 mmag, i.e., about four times smaller than in the discovery data. We do not detect the third mode found by Waelkens & Cuypers (1985) despite the fact that the detection threshold in the ASAS-3 photometry amounts to about 4 mmag, well below 7 mmag, the semi-amplitude of the third mode in the 1983 data. Apparently, the amplitudes of the two modes in V348 Nor, in particular, the main mode, declined between 1983 and the epochs of the ASAS-3 observations (2001–2006). This is confirmed by the Hipparcos data, where only the main mode with frequency 7.55778 d^{-1} is detected. Its H_p semi-amplitude amounts to about 16 mmag. The other modes are not detected, but the detection threshold is rather high in the Hipparcos data, amounting to about 9 mmag.

6. Discussion

It is not well known how common amplitude and period changes are among β Cephei stars. The main reason for this is the lack of homogeneous observations covering long time intervals. From the analysis of observations for stars with the longest observational records it seems, however, that, if detectable, changes of periods and amplitudes of modes excited in β Cephei stars have a typical time scale longer than a few months. In many cases it is much longer than a decade as in the well-documented case of 16 (EN) Lac (Jerzykiewicz & Pigulski 1996, 1999).

6.1. Changes of periods

The evidence for long-term period variations among β Cephei stars was summarised a few years ago by Jerzykiewicz & Pigulski (1998) and Jerzykiewicz (1999). One of the main reasons for the long-term monitoring of periods in β Cephei stars is the hope that evolutionary changes in these stars will be detected and confronted with the predictions of the theory. According to the theory (Eggleton & Percy 1973; Lesh & Aizenman 1974), in the core-hydrogen burning stage of evolution, where most β Cephei stars are believed to occur, the rate of period change, $\dot{P}$, should be smaller than 0.3 seconds per century and positive. Although this value is small, it is detectable provided that observations cover at least a decade. $\dot{P} > 0$ arises as a consequence of increase of stellar radius during the evolution on the main sequence.

Stars with small positive $\dot{P}$, consistent with theoretical predictions for core-hydrogen burning phase, are indeed observed (Jerzykiewicz 1999), although there are cases (BW Vul, σ Sco) where $\dot{P}$ is much larger than 0.3 s cen^{-1} which was used as an argument in favour of the hypothesis that they had already evolved off the main sequence (Pigulski 1992, 1993). In this group, there was also δ Cet. For this star, $\dot{P}$ was equal to 0.47 ± 0.09 s cen^{-1} (Jerzykiewicz et al. 1988), slightly too large for the main-sequence evolution (see Fig. 1 of Jerzykiewicz 1999). In view of the new observations, however, it is clear that for this star the change of period can no longer be interpreted in terms of a constant $\dot{P}$ (Jerzykiewicz 2007).

There are, however, β Cephei stars in which the period behaviour was much more complex. Jerzykiewicz (1999) listed three such stars: β CMa, 12 (DD) Lac, and 16 (EN) Lac. Indeed, the evolutionary changes of period may contribute to the observed period changes in these stars only partly because the changes are different for different modes. Moreover, for some modes the period was found subsequently to increase and decrease. The pattern of period changes for modes excited in V836 Cen (Fig. 9) resembles that observed in the three above-mentioned stars, especially 12 Lac (Pigulski 1994). Thus, V836 Cen may be regarded as the fourth member of this group of β Cephei stars with complex period behaviour. It will be shown in Paper II that one of the new β Cephei stars, HD 168050, also exhibits a complex period behaviour. All five stars from this group are multiperiodic. It seems therefore that when many modes are excited, some kind of mode interaction causes period and, as we shall comment below, amplitude changes.

In this context it is worth noting that in the study of period variations we assume that pulsations are coherent. In a general case, this might not be true. If random phase shifts are generated in a star, e.g., by the presence of other mode(s), period variations similar to those seen in 12 Lac and V836 Cen can be observed. For such stars we can expect to detect evolutionary period changes only on a time scale which would average random changes. For β Cephei stars this probably means centuries.

Period variations in β Cephei stars might be additionally complicated by the presence of a star in a wide binary system. In such a case, additional contribution to the apparent period changes comes from the light-time effect. This is indeed observed in β Cep (Pigulski & Boratyn 1992), σ Sco (Pigulski 1992) and possibly BW Vul (Pigulski 1993). As KK Vel is known to have a close visual companion at separation of about 0.″3, the large changes of period seen in Fig. 7, apparently in both directions, can be mostly due to the light-time effect.

6.2. Changes of amplitudes

Changes of amplitudes were reported for only a handful of β Cephei stars. Jerzykiewicz (1999) listed five stars with long-term amplitude variations: β CMa, 27 (EW) CMa, V381 Car, α Vir A, and 16 Lac. Evidence for amplitude change was also found for ν Cen (Ashoka & Padmini 1992; Schrijvers & Telting

2002) and for one mode in 12 Lac (Pigulski 1994). As modes in V836 Cen also show amplitude changes (Fig. 9), we conclude that all stars with complex period behaviour also show amplitude changes. The outstanding examples from this group are the primary of Spica (α Vir) in which pulsation amplitudes dropped to undetectable level or ceased altogether (Lomb 1978; Sterken et al. 1986) and 16 Lac which was monitored photometrically many times since the time of discovery. The changes of amplitudes and periods of its four dominant modes are therefore known very well (Jerzykiewicz & Pigulski 1996, 1999). Apart from V836 Cen, we report amplitude changes for BW Cru and V348 Nor. Note that both BW Cru and V348 Nor are not known as multiperiodic.

In this paper, combining ASAS-3 photometry with the archival data, we found evidence for period and amplitude changes in four known β Cephei stars. In addition, in Paper II, complex period changes in HD 168050 were found using only ASAS-3 data. This shows that period and amplitude changes might be quite common in β Cephei stars but, obviously, can be detected only if the data cover sufficient time intervals, typically more than a decade. Fortunately, ASAS is continuing and will be soon extended into the northern hemisphere. In addition, other photometric surveys are expected to provide abundant time-series data. In view of the fact that over 200 new β Cephei stars were detected in the ASAS-3 data, the sample of stars in which we will be able to monitor long-term changes of amplitudes and periods will increase considerably over the next decades.

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Online Material

Appendix A: Notes on individual stars

A.1. Stars from the list of Stankov & Handler (2005)

V350 Pup = HD 59864 = HIP 26500. This star was discovered as a double-mode β Cephei-type variable by Sterken & Jerzykiewicz (1990). Unfortunately, due to aliasing problems, the frequencies of the two modes they found, could not be indicated unambiguously.

The highest peak in the periodogram of the ASAS-3 data of V350 Pup slightly exceeds the detection limit and occurs at frequency $f = 4.23945$ d^{-1} (Fig. 2). This frequency coincides perfectly with the fourth frequency in the list of equally high peaks (4.240 d^{-1}) given by Sterken & Jerzykiewicz (1990). It is therefore very likely that this value represents the true pulsation frequency or its daily alias. The semi-amplitude in the ASAS-3 data amounts to 3.9 ± 0.6 mmag which is less than the value of 7.1–7.7 mmag reported by Sterken & Jerzykiewicz (1990). The latter observations were, however, carried out in the *B* band, while the ASAS-3 data were obtained in the *V* band, so that the amplitudes are not directly comparable. No significant peaks were found in the Hipparcos data for this star, but the detection threshold amounted to about 7 mmag.

YZ Pyx = HD 71913 = HIP 41586. The variability of YZ Pyx was discovered in Hipparcos data (Waelkens et al. 1998); subsequently the star was studied by Aerts (2000). She found a single frequency both in the Hipparcos and Geneva data, with the *V* semi-amplitude of 16 mmag. A single mode with a very similar amplitude was also found in the ASAS-3 data (Fig. 2, Table 2). All existing data (Hipparcos, Geneva and ASAS-3) of YZ Pyx are well represented by a single mode with a constant period of 0.2057818 ± 0.0000002 d.

IL Vel = HD 80383. ASAS-3 photometry and the variability record were already discussed by P05. However, since the time of publication of that paper, some new data were obtained by ASAS-3. Consequently, we provide a new solution, essentially in agreement with that of P05. The frequency spectrum of IL Vel is dominated by two high-amplitude modes, the only ones which were detected in the ASAS-3 data (Fig. 2). From the analysis of the archival data we conclude that the amplitudes and periods of these two main modes were stable during the last 30 years. The mean periods of these modes are equal to 0.18315764 ± 0.00000003 d and 0.18645460 ± 0.00000005 d. However, we confirm the suggestion made by Handler et al. (2003), that more modes are present in this star. This can be judged primarily from the analysis of the data of Heynderickx & Haug (1994). Unfortunately, these data suffer from a strong aliasing problem, so that the frequencies of the low-amplitude modes cannot be given unambiguously. The star certainly deserves a follow-up multi-site campaign, as it is potentially a very good target for asteroseismology.

V433 Car = HD 90288. This fast-rotating star was discovered to be variable in light by Lampens (1988), and then studied by Heynderickx (1992) who found four periodic terms in his photometry. Four modes were confirmed by Handler et al. (2003), although frequencies of some differed by 1 d^{-1} from the values given by Heynderickx (1992). Handler et al. (2003) also found one combination frequency. In the ASAS-3 data, we find only the two periodic terms with the largest amplitudes (Fig. 2). Their frequencies differ slightly from those given by Handler et al. (2003), but this may be a consequence of the fact that we did not fit the modes with low amplitudes which were below the detection threshold in the ASAS-3 data (4.6 mmag). The amplitudes of the two main modes agree to within the errors with those given by Handler et al. (2003).

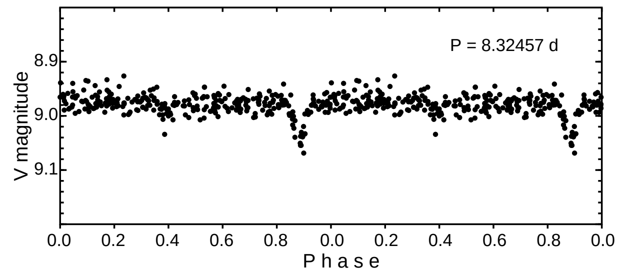

Fig. A.1. ASAS-3 data of V381 Car phased with the orbital period of 8.32457 d given by Freyhammer et al. (2005).

Stars in NGC 3293. Eleven β Cephei stars are known in this young open cluster (Balona 1977; Balona & Engelbrecht 1983; Heynderickx 1992; Balona 1994; Balona et al. 1997). All have magnitudes in the range covered by ASAS-3 data. Unfortunately, because of the limited spatial resolution of the ASAS-3 data (see Sect. 2), we detect photometric variability due to pulsations in only two of them, V401 Car and V403 Car.

V401 Car (NGC 3293-10) was discovered by Balona & Engelbrecht (1983) who reported a period of 0.176 d. Engelbrecht (1986) listed five modes, two of which were confirmed later by Heynderickx (1992). Balona (1994) also found two modes, but frequency of only one agreed with that of Heynderickx (1992). Finally, Balona et al. (1997) reported three frequencies. The frequencies given in these papers do not always agree, even if aliasing is taken into account. The mode which is listed most frequently is the mode with the highest amplitude, equal to about 10 mmag in *V*, having a frequency of 5.92 d^{-1}. We detect it in the ASAS-3 data, although at the detection limit (S/N = 4.0, see Fig. 2) and with amplitude of only 6 mmag, apparently lowered by contamination.

V403 Car (NGC 3293-16) was discovered by Balona & Engelbrecht (1983) as a star pulsating with a period of 0.249 d. Engelbrecht (1986) found the same dominant mode with frequency of 3.99 d^{-1} and a secondary one at $f = 4.92$ d^{-1}. Heynderickx (1992) re-analysed data obtained by Cuypers (1985) and found also two modes, with frequencies 3.9929 and 3.9147 d^{-1}. Finally, Balona (1994) and Balona et al. (1997) found a single mode with a frequency of 3.996 and 3.990 d^{-1}, respectively. The main mode has the *V*-filter semi-amplitude of about 25 mmag. We detect it in the ASAS-3 data (Fig. 3), although with smaller amplitude evidently due to contamination by nearby stars. As the yearly aliases are rather small in the ASAS-3 data, we conclude that the value of 3.9929 d^{-1} reported by Heynderickx (1992), is a yearly alias of the true frequency. The secondary mode is possibly real as it was detected in two independent data sets; its frequency found by Heynderickx (1992), is a daily alias of that given by Engelbrecht (1986). It could not be detected in the ASAS-3 data due to its small amplitude.

V381 Car (NGC 3293-5) = HD 92024 is an 8.32-day detached eclipsing system with a β Cephei-type primary. It was discovered by Engelbrecht (1986) and then studied by Engelbrecht & Balona (1986), Jerzykiewicz & Sterken (1992) and recently, by Freyhammer et al. (2005). We do not detect pulsations in this star. However, the eclipses, with lowered depths, again due to contamination, can be seen in the phased ASAS-3 light curve (Fig. A.1).

KZ Mus = HD 109885 = HIP 61751. The star was noted as variable by Tobin et al. (1994). The variability was confirmed in the Hipparcos data (Waelkens et al. 1998; Aerts 2000). The most recent study of the star was that of Handler et al. (2003)

who found four independent modes in the multicolour photometry of KZ Mus. We find three modes in the ASAS-3 data (Fig. 3). Their amplitudes and frequencies agree very well with those of Handler et al. (2003), see Table 2. We did not detect the fourth mode; the frequency of the highest peak in the periodogram of residuals, however, equal to 5.7103 d^{-1}, is very close to the frequency of the fourth mode found by Handler et al. (2003).

Stars in NGC 4755. This is another young open cluster in the southern hemisphere known to contain a large number, namely ten, β Cephei-type stars (Jakate 1978; Shobbrook 1984; Koen 1993; Balona & Koen 1994; Stankov et al. 2002). We find pulsations in only one β Cephei star in this cluster, namely BW Cru, already discussed in Sect. 5. In addition, for CV Cru = NGC 4755-I, the known mode with f = 5.585 d^{-1} is marginally detected with S/N = 3.8. For the remaining stars, the ASAS-3 photometry either does not exist or has large photometric errors.

V856 Cen = HD 112481 = HIP 63250. The variability of V856 Cen was discovered by Waelkens & Heynderickx (1989). They found two periodic terms. The first had a frequency of 3.9287 d^{-1}, but the frequency of the other, 3.851 d^{-1}, was uncertain. The star was subsequently studied by Heynderickx (1992), who confirmed both modes and derived their frequencies, 3.92870 and 3.85181 d^{-1}. We detected only the main mode (Fig. 3) with frequency 3.92867 ± 0.00002 d^{-1}, in very good agreement with previous determinations. The main mode is also easily detected in the Hipparcos data with a frequency of 3.92860 ± 0.00005 d^{-1}.

V349 Nor = HD 145794. The variability of HD 145794 was discovered by Waelkens & Heynderickx (1989). Two periodic terms were found. The first had frequency of 6.2507 d^{-1}; for the other, due to aliasing, there were two possibilities: 4.2101 or 5.2129 d^{-1}. We find the main mode with frequency 6.25354 d^{-1} (Fig. 3), corresponding to 1 year^{-1} alias of the frequency found by Waelkens & Heynderickx (1989). For the second mode, S/N = 4.3, barely exceeding the limiting value. The frequency amounts to 5.21316 d^{-1}, in agreement with the second value given by the discoverers.

Stars in NGC 6231. This is the third southern open cluster with a large number (six) of known β Cephei-type stars (Shobbrook 1979; Balona & Shobbrook 1983; Balona & Engelbrecht 1985; Balona & Laney 1995; Arentoft et al. 2001). As for NGC 3293 and NGC 4755, the magnitudes of β Cephei stars in this cluster are within the range covered by the ASAS-3 observations. Unfortunately, we did not detect any pulsations for these stars. For some of them the data were too sparse, for the other, the photometric errors were too large.

V1035 Sco = HD 156327 B = HIP 84655. HD 156327 is a well-known WC7-type Wolf-Rayet star WR 86. Due to the presence of absorption lines in the spectrum, the star was suspected to have a companion (Roberts 1962; Smith 1968). The star was also noted as a visual binary by Jeffers et al. (1963). The presence of a close companion was excluded because no clear radial-velocity variations were found (Massey et al. 1981), but a visual component was confirmed by means of speckle interferometry (Hartkopf et al. 1993), and later with the HST (Niemela et al. 1998; Lépine et al. 2001). The components, very similar in brightness, are separated by about 0.″23. The secondary is a B0 III star (Lépine et al. 2001).

Photometric variability of HD 156327 with a period of about 3 hours was discovered by Monderen et al. (1988) from a single-night observations in the Walraven *WBLUV* system. Similar variability was observed by van Genderen et al. (1990), and the variations were at first attributed to the WR-type primary. However, van Genderen et al. (1991) considered the possibility that the B0-type secondary is a β Cephei star and derived 0.1385 ± 0.0002 d (f = 7.22 d^{-1}) for the period of the photometric variations. Owing to the evident variability, the star was named V1035 Sco (Kazarovets & Samus 1997). A detailed photometric and spectroscopic study was later performed by Paardekooper et al. (2002). They concluded that the short-period photometric variability of V1035 Sco should be attributed to the secondary component and can be described by two modes with frequencies 6.914 and 7.236 d^{-1}.

In the ASAS-3 data, which are quite numerous for this star, we detect unambiguously three modes (Fig. 4, Table 2). If the frequency resolution of the observations made by Paardekooper et al. (2002) is taken into account, it can be stated that the first two modes are the same as those found by Paardekooper et al. (2002).

A periodogram of Hipparcos data of V1035 Sco shows only an increased power in the region of the detected modes, but the photometry is too poor to detect any mode.

V831 Ara = HD 156662. Photometric variability of V831 Ara was discovered by Waelkens & Cuypers (1985) who found three modes in the Geneva photometry of this star, with semi-amplitudes of 8, 6, and 5.5 mmag in V. The frequencies were later re-calculated by R. Peetermans, as reported by Heynderickx (1992), and were found to be equal to 5.30269, 5.89065, and 5.92120 d^{-1}.

We also find three modes in the ASAS-3 photometry of this star (Fig. 4). The first mode we detect has frequency f_1 = 6.30519 d^{-1}, a daily alias of the frequency given by Heynderickx (1992). After prewhitening with f_1, the two remaining modes were recovered as well, with frequencies equal to 5.88907 and 5.92138 d^{-1}, in agreement with Heynderickx (1992). In fact, a daily alias with frequency of about 3.89 d^{-1} was slightly higher than that at 5.889 d^{-1}, but it was 2 d^{-1} apart, so we adopted the value closest to that of Heynderickx (1992). Since both sources of data suffer from severe daily aliasing, it is difficult to decide which of the alias frequencies for f_1 is correct.

V2371 Oph = HD 157485 = HIP 85189. The star was discovered in the Hipparcos data by Aerts (2000). She found two modes with frequencies equal to 4.521 and 4.464 d^{-1}, V amplitudes of 24 and 14 mmag, identified as ℓ = 1 and a radial mode, respectively. We also detect two modes, with the same frequencies and amplitudes (Fig. 4, Table 2).

NSV 24078 = HD 164340 = HIP 88352. A possible variability of radial velocity of HD 164340 was already noted by Kilkenny et al. (1975), and then confirmed by Kilkenny & Hill (1975). The star's photometric variability was found in the Hipparcos data. It was included in the Hipparcos catalogue as an unsolved variable and designated as NSV 24078. In the Hipparcos photometry of this star, Molenda-Żakowicz & Połubek (2005) found two periodic terms with frequencies 6.53876 and 6.37776 d^{-1}.

The ASAS-3 photometry of NSV 24078 was already analysed by P05 revealing the same two modes and possibly a third one. With additional data from ASAS-3, we provide a new solution here. The third mode is now confirmed (Fig. 4); its frequency is a daily alias of that mentioned by P05. In addition, the fourth mode, at frequency 7.74246 d^{-1}, was detected.

V4382 Sgr = HD 165812 = HIP 88884. The star was discovered in the Hipparcos photometry by Waelkens et al. (1998). From Geneva photometry, Aerts (2000) found two modes. The frequency of the main mode, however, derived from the Hipparcos data (5.9164 d^{-1}) differed from that obtained from the Geneva photometry (5.686 d^{-1}). With the ASAS-3 data, we confirm the two modes found by Aerts (2000). They have practically

the same amplitudes in the ASAS-3 photometry as in the Geneva data. The frequency of the second mode is, however, the daily alias of that found by Aerts (2000) and amounts to 5.58497 d^{-1}. In addition, we found a third mode (Fig. 5, Table 2).

V4159 Sgr = HD 166540 = HIP 89164. This B0.5 IV-type star (Morgan et al. 1953) was discovered to be variable by Waelkens et al. (1991). They found one dominant mode with a frequency of 4.2920 d^{-1} and an indication for more modes with frequencies in the range between 4.2 and 4.5 d^{-1}. The secondary and tertiary modes reported by Waelkens et al. (1991) had frequencies of 4.2303 and 4.3996 d^{-1}. We found five modes in the ASAS-3 photometry of this star (Fig. 5). Although the frequencies also fall in the range between 4.24 and 4.36 d^{-1}, none agrees with those given by Waelkens et al. (1991). The five modes form a close pair and a triplet. The pair is separated by 0.0144 d^{-1}, while the separations in the triplet equal 0.0027 and 0.0052 d^{-1}. The former value is equal to 1 yr^{-1}, the latter is roughly twice as long. If the modes are real, this is unfavourable, although the yearly aliases in the spectral window of the ASAS-3 data of V4159 Sgr are not very strong: about 60% of the height of the main peak. Nevertheless, the frequencies of the triplet should be treated with caution.

Unfortunately, the Hipparcos data do not resolve the problem. They are too few for detecting any mode unambiguously. In the periodogram of the Hipparcos data, only an excess of power can be seen in the range of frequencies where the modes found with the ASAS-3 data occur.

V1449 Aql = HD 180642 = HIP 94793. The ASAS-3 photometry was previously analysed by P05. With some new data acquired since this publication of this paper, we present a new solution which is in very good agreement with the previous one: a single, large-amplitude mode is detected (Fig. 5, Table 2).

SY Equ = HD 203664. This is another star found to be variable by Hipparcos and then re-observed by Aerts (2000). As for V1449 Aql, its ASAS-3 photometry was previously analysed by P05. We provide a new solution for this star, again in agreement with the previous one. New Geneva photometry of SY Equ was also recently obtained by Aerts et al. (2006). In addition to the known high-amplitude mode, they detected two low-amplitude ones. The amplitudes are, however, lower than the detection threshold in the ASAS-3 data (5.6 mmag), so we were unable to confirm them.

HN Aqr = PHL 346. This B1-type star is a very interesting case because of its high Galactic latitude ($b = -58°$) and Population I abundances (Keenan et al. 1986; Ryans et al. 1996). It opened a discussion on the possibility of star formation far outside the Galactic plane (e.g. Keenan 1986, 1992). For HN Aqr, it is still not certain if the star was formed outside the Galactic plane (Hambly et al. 1996; Lynn et al. 2002) or is a runaway object (Ramspeck et al. 2001).

HN Aqr was found to be photometrically variable by Waelkens & Rufener (1988) who observed the star in the Geneva system. They found a single mode with a period of 0.1522 d. This variability was confirmed by Kilkenny & van Wyk (1990) in *BV* photometry. The variability was also detected in the ultraviolet flux and radial velocities (Dufton et al. 1998).

The analysis of the ASAS-3 data also reveals a single mode with the same frequency and amplitude as found by previous investigators (Fig. 5).

A.2. Stars found by Pigulski (2005)

As mentioned in the Introduction, the published ASAS-3 catalogue already contained a number of new β Cephei stars. Pigulski (2005) verified the results of the automatic classification finding that the catalogue contains 14 new β Cephei stars. He also provided multi-frequency solutions for these stars. Since the publication of that paper, data for the equatorial stars were made available (Pojmański et al. 2005). In addition, new observations were acquired for all stars. We therefore updated the solutions for 14 β Cephei stars found by P05. They are presented in Table 3. We do not show updated periodograms because they are, in general, very similar to those already presented by P05.

For seven stars, the solutions are practically the same as those provided by P05. For the remaining seven stars, there are some differences: For HD 133823, the peak at about 0.5 d^{-1} was suspected by P05 to be spurious. With the new data added, the peak stands out more clearly in the periodogram, so we included it in the solution. In addition, two other modes in its vicinity were detected. The values of S/N for the three low-frequency peaks amount to 6.4, 5.5, and 4.9, i.e., clearly above the detection threshold. The frequencies of the three peaks are in the range of 0.50–0.61 d^{-1}, suggesting either *g*-mode pulsations or variability related to rotation. In the former case, HD 133823 would be an interesting example of a hybrid β Cephei/SPB type of variability.

For CPD −50°9210 we find a third mode. It is interesting to note that $2(f_3 - f_2) \approx (f_2 - f_1)$.

A new mode was also found for HDE 328906. Due to aliasing, its frequency is uncertain, however. Although the peak at 8.264 d^{-1} is the highest, the daily aliases at 6.261 and 5.259 d^{-1} are almost equally high. We finally adopted the frequency of 5.259 d^{-1} for f_2 because it is closest to the frequency of the main mode. This needs to be verified with future observations, however.

For HD 152077, we decided not to include the f_4 mode listed by P05 in the new solution because after prewhitening with the three modes and the combination frequency, the aliasing problem becomes very severe. It is, however, obvious, that at least two more low-amplitude modes are present in this star.

For HD 155336, P05 provided a solution with three modes. The new solution also includes three modes, but two, f_2 and f_3, have frequencies different from those given by P05. The difference is the result of a complicated structure of the window function. This is because 60% of the ASAS-3 data for HD 155336 were made during 6 observing nights spread over 20 days. However, if these nights are omitted, the same three modes as given in Table 3 are detected. This strengthens the reliability of the new solution.

There was also a problem with the correct identification of aliases for HD 165582, as discussed in detail by P05. Fortunately, over 400 new datapoints were obtained for this star. This allows us to give a new, presumably correct, solution. The new f_2 is roughly equal to the old f_2 minus 2 d^{-1}, whereas the new f_3 equals to the old f_4 plus 2 d^{-1}. The f_2 and f_3 modes are very close, the beat period between them equals to about 250 days.

Finally, for ALS 5040, the new solution substitutes a daily alias for the old frequency f_3.

A.3. Stars found by Handler (2005)

As we mentioned in the Introduction, Handler (2005) identified five new β Cephei stars in the ASAS photometry, four in the *I*-filter ASAS-2 data and one, HD 191531, in the ASAS-3 data. The latter was not found by P05 because the star was included in the published catalogue after his analysis. Also, the four stars found by Handler (2005) in the ASAS-2 data were not listed as variable in the published ASAS-3 catalogue of variable stars. We analyse their ASAS-3 photometry in this paper. The stars

are included in Table 1, the parameters of the sine-curve fits to the ASAS-3 photometry are given in Table 4, and their Fourier periodograms are shown in Fig. 6.

For HD 100495 = ALS 2386 we find the same mode as Handler (2005) in the ASAS-2 data, but, in addition, two low-amplitude modes. The frequency f_3 is probably the daily alias of the f_2 mode suspected by Handler (2005). For CPD $-61°3314$ = ALS 2714 we detect the same four modes and a combination frequency as Handler (2005) but in addition, another combination mode, $f_2 + f_3$. It is interesting that all modes have relatively large amplitudes for a β Cephei star. For each of the remaining three stars, ALS 2798, ALS 2877, and HD 191531 = HIP 99327, we find one mode less than Handler (2005).

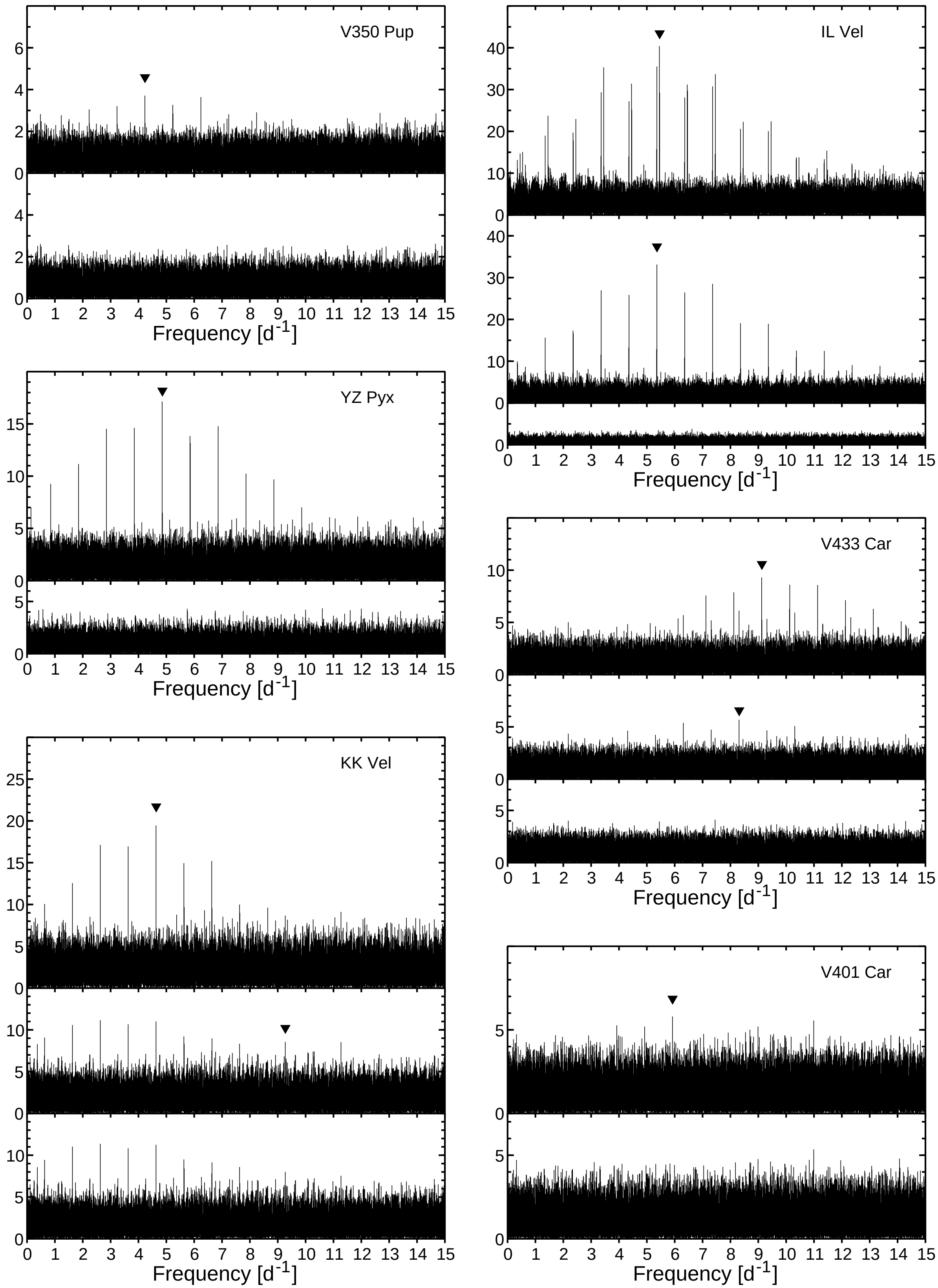

Fig. 2. Fourier periodograms of the ASAS-3 data of six β Cephei-type stars discussed in the paper: V350 Pup, YZ Pyx, KK Vel, IL Vel, V433 Car, and V401 Car. The panels show periodograms after consecutive steps of prewhitening. Frequencies of the detected modes are indicated by inverted triangles. Ordinate is the semi-amplitude expressed in mmag.

Table 2. Parameters of the sine-curve fits to the V magnitudes of the known β Cephei-type stars listed in Table 1. $N_{\rm obs}$ is the number of observations. The initial epoch, T_0, equals 2450000.0. The other parameters are the following: $T^i_{\rm max}$ is the time of maximum light for ith mode, $\sigma_{\rm res}$, standard deviation of the residuals, DT, detection threshold defined as S/N = 4.

Star name	Freq.	$N_{\rm obs}$	f_i [d^{-1}]	A_i [mmag]	$T^i_{\rm max} - T_0$ [d]	$\sigma_{\rm res}$ [mmag]	DT [mmag]
V350 Pup	f_1	529	4.23945(5)	3.9(06)	3016.0753(58)	9.8	3.0
YZ Pyx	f_1	305	4.85955(2)	17.1(09)	2922.0226(17)	11.2	4.5
KK Vel	f_1	282	4.63651(4)	18.5(17)	3238.1778(33)	20.7	8.8
	$2f_1$		9.27302	3.6(17)	3238.0884(83)		
IL Vel	f_1	457	5.45978(1)	37.5(08)	2930.4177(06)	11.9	4.0
	f_2		5.36325(1)	34.4(08)	2930.2800(07)		
V433 Car	f_1	342	9.12945(3)	8.7(10)	2896.0042(18)	12.0	4.6
	f_2		8.31616(5)	5.8(09)	2896.0604(31)		
V401 Car	f_1	302	5.92302(6)	5.7(11)	2954.4643(52)	13.7	5.6
V403 Car	f_1	262	3.99009(4)	16.6(21)	3071.1564(50)	24.0	10.4
KZ Mus	f_1	632	5.86402(1)	37.8(07)	2817.6862(05)	12.6	3.5
	f_2		5.95070(1)	15.9(07)	2817.6471(12)		
	f_3		6.18750(2)	10.9(07)	2817.6239(17)		
BW Cru	f_1	302	4.88458(4)	10.3(12)	2909.4986(38)	14.5	5.9
V856 Cen	f_1	273	3.92867(2)	16.3(07)	2819.7251(20)	8.6	3.7
V836 Cen		290		see Table 6		15.8	6.6
V349 Nor	f_1	387	6.25355(3)	6.1(07)	2961.9822(29)	9.4	3.2
	f_2		5.21317(6)	3.9(07)	2962.0157(53)		
V348 Nor	f_1	354	6.90033(3)	10.8(08)	2784.2783(17)	10.3	3.9
	f_2		7.55795(5)	5.4(08)	2784.2650(31)		
V1035 Sco	f_1	678	6.84316(3)	8.5(06)	3050.3266(16)	9.9	3.2
	f_2		7.46406(3)	9.7(06)	3050.3271(12)		
	f_3		7.98473(4)	5.8(06)	3050.2980(18)		
V831 Ara	f_1	251	6.30519(3)	8.1(08)	3012.4817(23)	8.4	3.9
	f_2		5.88907(5)	4.9(08)	3012.4255(42)		
	f_3		5.92138(5)	4.4(08)	3012.5105(45)		
V2371 Oph	f_1	457	4.52105(2)	23.2(09)	3012.8319(13)	12.8	4.8
	f_2		4.46677(2)	14.3(09)	3012.8161(21)		
NSV 24078	f_1	323	6.37773(1)	27.7(08)	2821.0650(08)	10.4	4.1
	f_2		6.53875(1)	22.0(08)	2821.1148(09)		
	f_3		5.93043(4)	6.5(08)	2821.1187(34)		
	f_4		7.74246(6)	4.8(08)	2821.1315(36)		
V4382 Sgr	f_1	713	5.68565(2)	14.3(05)	2968.9834(09)	8.0	2.4
	f_2		5.58499(2)	11.2(05)	2969.0571(11)		
	f_3		6.29401(5)	3.3(05)	2969.0984(33)		
V4159 Sgr	f_1	581	4.25239(3)	7.6(06)	2946.1190(28)	7.6	3.1
	f_2		4.34200(3)	9.5(05)	2946.0906(18)		
	f_3		4.35640(3)	6.3(05)	2946.1130(28)		
	f_4		4.24964(3)	7.8(06)	2946.1301(28)		
	f_5		4.25765(6)	3.9(05)	2946.1956(46)		
V1449 Aql	f_1	223	5.48694(1)	37.4(10)	3005.4092(08)	10.4	4.9
SY Equ	f_1	131	6.02877(2)	30.1(11)	2999.7624(10)	9.0	5.6
HN Aqr	f_1	347	6.56525(3)	20.7(22)	2854.1722(25)	28.3	10.8

Table 3. Parameters of the sine-curve fits to the ASAS-3 V magnitudes of 14 β Cephei-type stars found by Pigulski (2005). The headings are the same as in Table 2.

Star name	Freq.	N_{obs}	f_i [d^{-1}]	A_i [mmag]	$T^i_{max} - T_0$ [d]	σ_{res} [mmag]	DT [mmag]
CPD −62°2707	f_1	458	7.058918(04)	55.7(09)	2845.4709(04)	13.4	4.5
	$2f_1$		14.117836	9.6(09)	2845.5446(11)		
HD 133823	f_1	351	5.680441(06)	53.7(11)	2870.6894(05)	13.6	5.3
	f_2		0.50382(4)	8.4(11)	2870.429(39)		
	f_3		0.60818(5)	7.3(11)	2870.045(38)		
	f_4		0.59951(5)	6.5(11)	2870.819(43)		
CPD −50°9210	f_1	365	4.866871(10)	39.7(13)	2898.0067(11)	17.1	6.0
	f_2		4.87937(2)	20.3(13)	2897.8218(21)		
	f_3		4.88575(6)	6.8(13)	2897.9157(62)		
HDE 328862	f_1	329	4.948818(06)	81.1(15)	2882.8172(06)	18.6	7.3
	f_2		4.92461(3)	15.7(15)	2882.9150(31)		
	f_1+f_2		9.87343	10.4(15)	2882.8640(23)		
	f_3		5.39896(5)	9.3(15)	2882.7266(46)		
CPD −46°8213	f_1	301	4.460151(10)	66.1(21)	2923.6372(11)	25.3	10.3
HDE 328906	f_1	341	5.630731(15)	42.8(24)	2902.1974(16)	30.5	11.6
	f_2		5.25868(5)	14.3(23)	2902.2620(51)		
HD 152077	f_1	457	4.911492(07)	48.8(11)	2717.8316(08)	16.7	5.6
	f_2		4.851642(12)	27.0(11)	2717.7484(14)		
	f_3		4.88636(2)	17.3(11)	2717.8499(21)		
	f_1+f_2		9.76313	7.4(11)	2717.7891(25)		
HD 152477	f_1	395	3.773746(08)	34.8(09)	2891.5274(11)	12.1	4.4
HD 155336	f_1	677	5.531722(08)	46.7(08)	3059.0981(05)	14.7	5.3
	f_2		5.45701(3)	13.0(09)	3059.0483(20)		
	f_3		5.06712(3)	9.9(09)	3058.9610(26)		
HD 165582	f_1	776	4.747267(12)	36.2(11)	3398.4084(10)	18.1	5.9
	f_2		5.38372(3)	17.2(11)	3398.3529(19)		
	f_3		5.38766(4)	11.8(11)	3398.3701(28)		
	f_4		4.72497(3)	11.1(11)	3398.3376(34)		
	f_1+f_4		9.47223	8.9(10)	3398.3792(18)		
HD 167743	f_1	358	4.823723(08)	41.2(10)	2825.7459(08)	13.5	5.1
	f_2		5.09694(2)	25.5(11)	2825.8195(13)		
	f_3		4.97579(3)	11.7(11)	2825.7717(28)		
ALS 5036	f_1	596	4.917347(07)	56.5(11)	2822.1409(06)	18.2	6.1
	f_2		4.91915(3)	12.5(11)	2822.0922(28)		
ALS 5040	f_1	435	4.973834(11)	47.5(16)	2825.4432(10)	21.8	7.5
	f_2		5.07193(3)	18.6(15)	2825.5043(25)		
	f_3		5.52310(5)	12.4(15)	2825.3553(43)		
BD −14°5057	f_1	385	4.163675(07)	44.5(09)	2823.1940(08)	12.5	4.5

Table 4. Parameters of the sine-curve fits to the ASAS-3 V magnitudes of five β Cephei-type stars found by Handler (2005). The headings are the same as in Table 2.

Star name	Freq.	N_{obs}	f_i [d^{-1}]	A_i [mmag]	$T^i_{max} - T_0$ [d]	σ_{res} [mmag]	DT [mmag]
HD 100495	f_1	647	5.935344(08)	26.9(08)	2849.6155(08)	13.9	3.7
	f_2		8.33112(5)	4.4(08)	2849.5807(35)		
	f_3		5.81785(6)	4.1(08)	2849.5591(53)		
CPD −61°3314	f_1	379	4.598425(08)	50.3(13)	2915.1919(09)	18.0	6.1
	f_2		4.540054(11)	31.0(13)	2915.0874(15)		
	f_3		4.57789(2)	25.4(13)	2915.1198(18)		
	f_4		4.55636(2)	20.3(13)	2915.2895(23)		
	f_1+f_2		9.138479	16.0(13)	2915.1315(14)		
	f_2+f_3		9.11794	8.6(13)	2915.2070(27)		
ALS 2798	f_1	312	4.69547(2)	50.1(24)	2855.0179(16)	28.5	11.4
	f_2		4.68777(2)	31.4(23)	2854.9120(25)		
	f_3		4.44150(5)	14.9(23)	2854.9022(56)		
ALS 2877	f_1	315	5.28745(2)	52.3(23)	2852.2556(13)	28.5	11.4
	f_2		5.30272(3)	25.4(23)	2852.3951(27)		
HD 191531	f_1	95	6.08590(3)	27.5(16)	3168.8461(15)	10.9	7.9

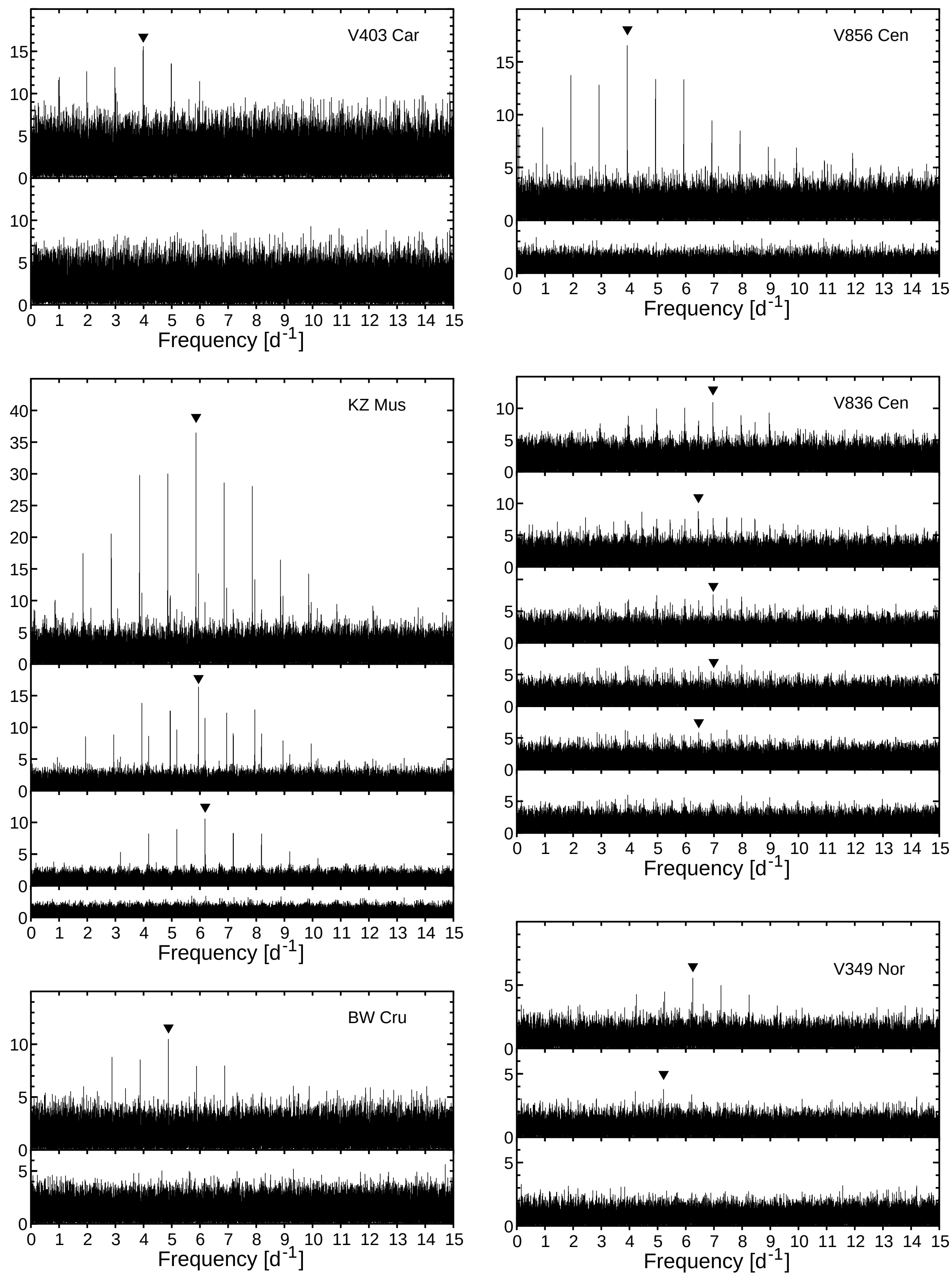

Fig. 3. The same as in Fig. 2, but for the next six β Cephei stars: V403 Car, KZ Mus, BW Cru, V856 Cen, V836 Cen, and V349 Nor.

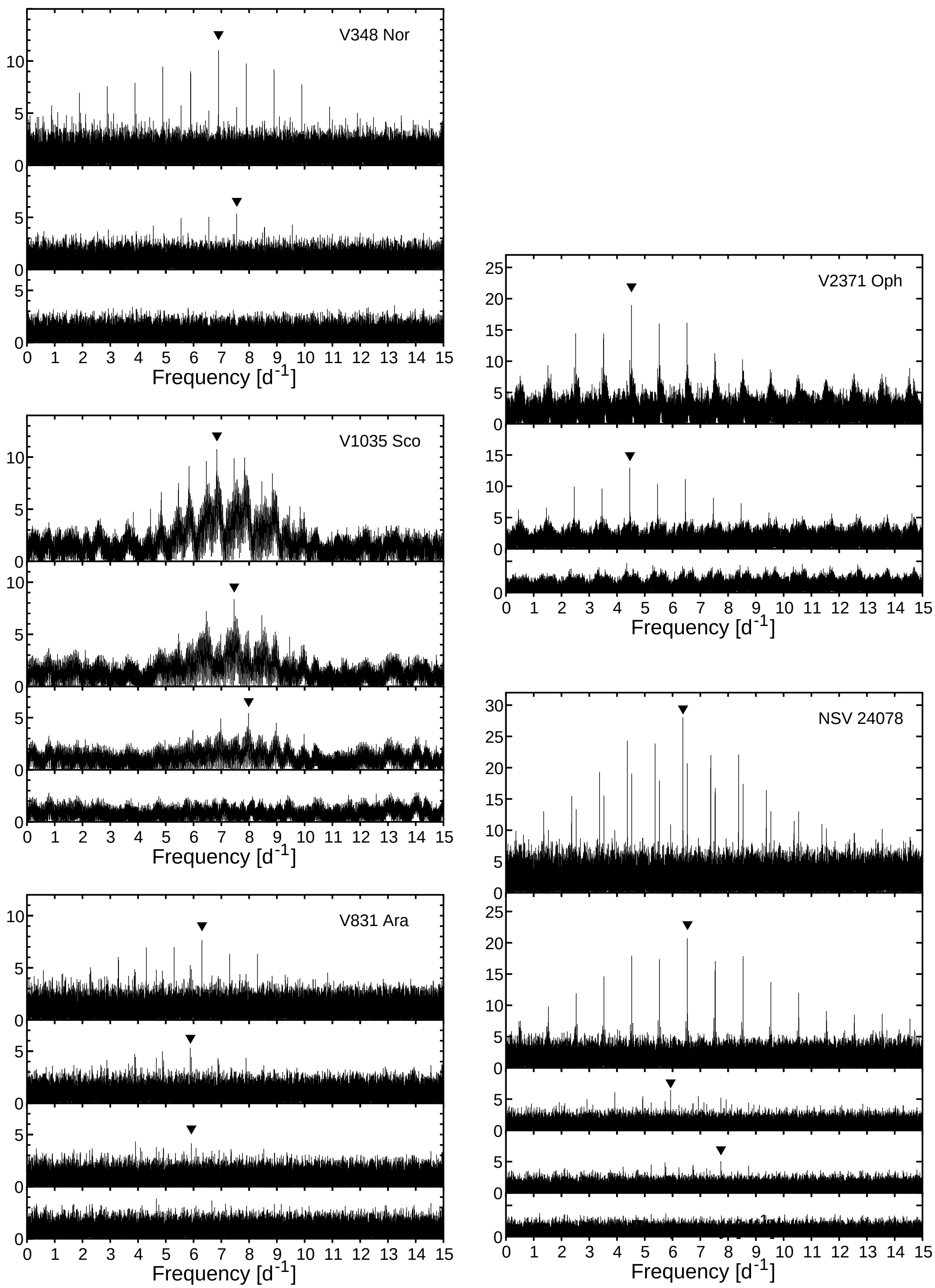

Fig. 4. The same as in Fig. 2, but for V348 Nor, V1035 Sco, V831 Ara, V2371 Oph, and NSV 24078.

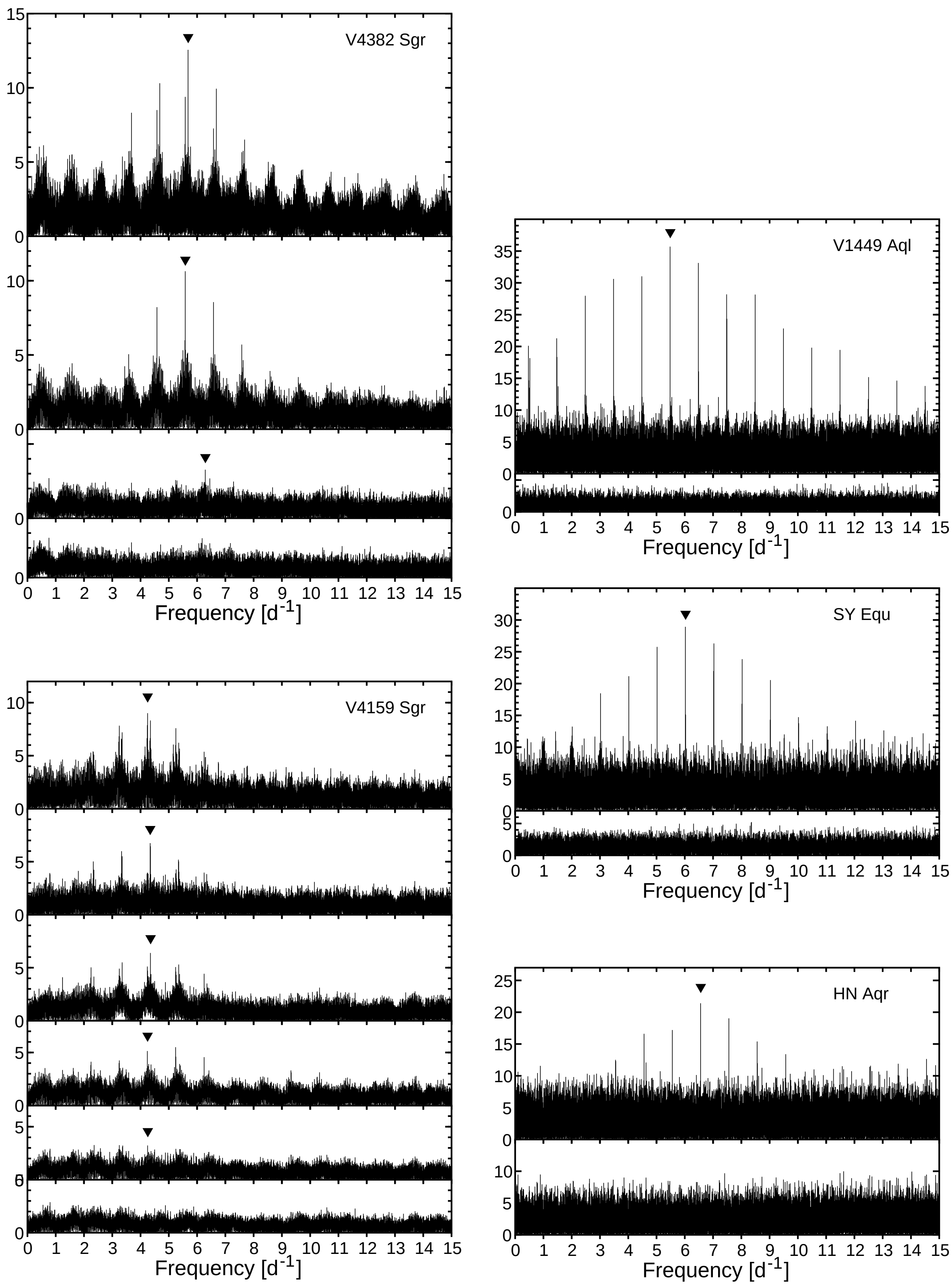

Fig. 5. The same as in Fig. 2, but for V4382 Sgr, V4159 Sgr, V1449 Aql, SY Equ, and HN Aqr.

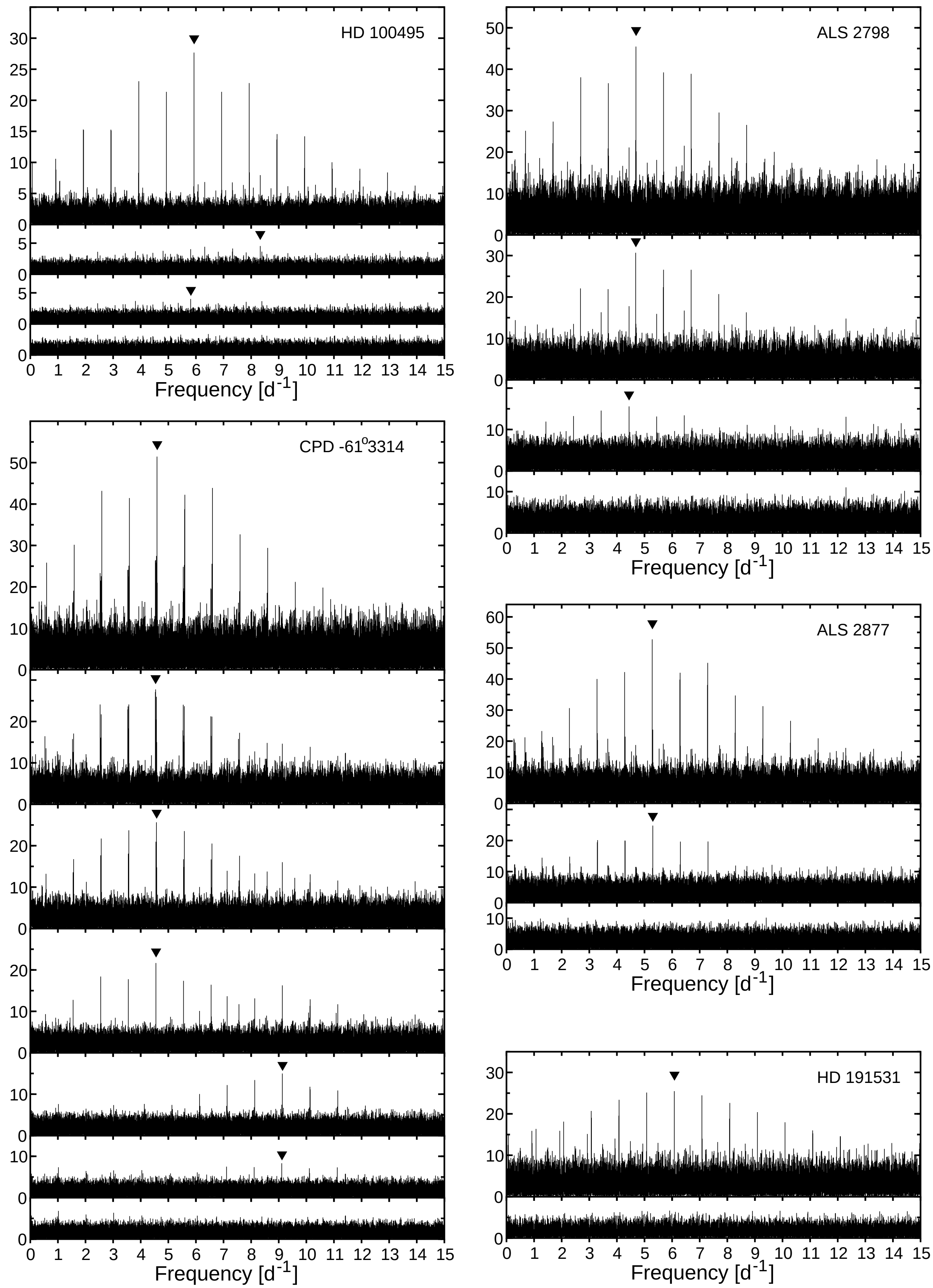

Fig. 6. The same as in Fig. 2, but for five stars discovered by Handler (2005): HD 100495, CPD −61°3314, ALS 2798, ALS 2877, and HD 191531.

Table 5. Mean amplitude ratios for the six modes of V836 Cen. Numbers in parentheses denote r.m.s. errors of the preceding numbers with the preceding zeroes omitted.

Mode	Frequency [d^{-1}]	A_{B1}/A_U	A_B/A_U	A_{B2}/A_U	A_{V1}/A_U	A_V/A_U	A_G/A_U
f_1	6.461752(18)	0.838(32)	0.829(31)	0.783(26)	0.754(27)	0.805(30)	0.766(31)
f_2	6.978314(12)	0.717(20)	0.716(18)	0.703(19)	0.703(37)	0.664(32)	0.651(26)
f_3	6.449609(07)	0.871(26)	0.852(28)	0.865(18)	0.776(20)	0.775(25)	0.769(39)
f_4	6.990409(26)	0.746(27)	0.774(33)	0.692(26)	0.676(55)	0.699(24)	0.686(36)
f_5	6.590951(13)	0.633(24)	0.590(32)	0.532(39)	0.548(32)	0.518(21)	0.501(34)
f_6	6.966151(18)	0.646(41)	0.632(65)	0.666(31)	0.585(42)	0.631(43)	0.591(45)

Table 6. Semi-amplitudes and the times of maximum light derived from sine-curve fits to 13 short datasets of V-filter observations of V836 Cen. Repeatable integral parts of the epochs are replaced by '—' for f_2 to f_6. The r.m.s. errors are given underneath the values. See text for details.

	Semi-amplitudes [mmag]						T^i_{max} – HJD 2440000.0					
Subset	f_1	f_2	f_3	f_4	f_5	f_6	f_1	f_2	f_3	f_4	f_5	f_6
1	16.0	8.5	10.9	9.4	3.1	5.1	3110.6581	—.6591	—.6258	—.7113	—.7270	—.7106
	2.2	2.1	2.1	1.9	2.1	2.0	0.0034	0.0056	0.0049	0.0044	0.0159	0.0103
2	11.9	5.8	8.4	11.6	5.8	6.8	4062.3987	—.3132	—.3071	—.3975	—.3427	—.3559
	1.4	1.5	1.3	1.3	1.4	1.4	0.0028	0.0055	0.0040	0.0024	0.0055	0.0049
3	12.7	10.0	11.1	8.6	5.0	9.0	4717.3292	—.3192	—.2345	—.2959	—.3337	—.2491
	0.5	0.5	0.5	0.5	0.5	0.5	0.0009	0.0011	0.0010	0.0012	0.0022	0.0012
4	11.4	10.5	10.9	9.6	5.6	3.5	6233.3441	—.4365	—.4713	—.3412	—.3536	—.3801
	0.6	0.6	0.6	0.6	0.6	0.6	0.0014	0.0014	0.0014	0.0015	0.0027	0.0041
5	11.2	14.3	8.4	9.8	4.3	6.9	7288.4910	—.4349	—.4131	—.4836	—.4324	—.3502
	0.8	0.9	0.8	0.8	0.8	0.8	0.0018	0.0013	0.0024	0.0019	0.0046	0.0028
6	10.7	9.8	9.2	13.6	4.9	7.1	7621.6837	—.7594	—.7675	—.6712	—.7743	—.6779
	0.7	0.7	0.7	0.7	0.7	0.7	0.0015	0.0015	0.0017	0.0011	0.0032	0.0021
7	11.0	15.8	8.9	11.2	6.7	3.9	8730.3661	—.3419	—.3647	—.3312	—.2656	—.3307
	0.9	0.9	0.9	0.9	0.9	0.9	0.0019	0.0013	0.0024	0.0018	0.0032	0.0052
8	12.3	14.1	10.4	10.0	5.2	3.2	9068.8205	—.6783	—.6745	—.8009	—.7520	—.7778
	0.7	0.7	0.8	0.8	0.7	0.8	0.0015	0.0012	0.0018	0.0017	0.0036	0.0054
9	11.6	7.4	8.6	13.3	7.5	3.2	9478.6050	—.6563	—.6129	—.6537	—.7150	—.6527
	1.0	1.0	1.0	0.9	1.0	0.9	0.0020	0.0028	0.0028	0.0016	0.0030	0.0065
10	10.2	6.0	6.9	11.2	4.6	4.4	9842.4294	—.3533	—.3504	—.3102	—.3975	—.3260
	1.0	1.1	1.0	1.0	1.0	1.1	0.0025	0.0039	0.0038	0.0022	0.0056	0.0054
11	7.7	18.6	7.4	14.3	1.1	12.2	12013.9393	—4.0663	—3.9638	—4.0419	—3.9470	—3.9675
	2.2	2.3	2.2	2.3	2.2	2.1	0.0068	0.0029	0.0073	0.0035	0.0451	0.0040
12	8.8	3.4	11.0	6.5	5.6	9.5	12702.7469	—.7800	—.8245	—.8365	—.8142	—.8489
	1.6	1.6	1.6	1.9	1.6	1.6	0.0047	0.0109	0.0037	0.0052	0.0071	0.0040
13	6.9	5.5	9.0	3.1	5.6	11.5	13323.9475	—.9588	—.9643	—.9765	—.9914	—.9913
	1.7	1.7	1.6	1.7	1.7	1.6	0.0059	0.0070	0.0045	0.0125	0.0070	0.0035